Supermassive black hole mergers and cosmological evolution

Marta Volonteri

IoA Cambridge

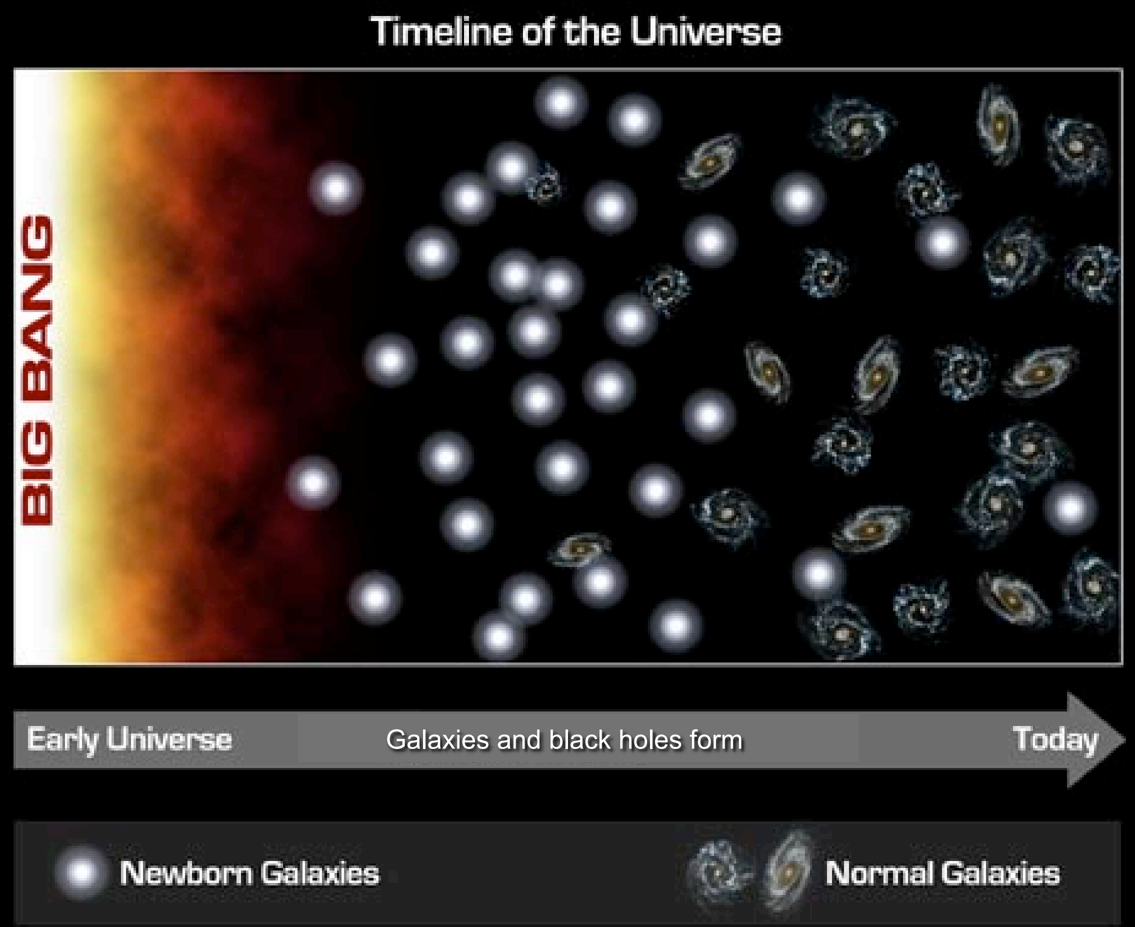


Image credit: NASA/JPL-Caltech

Outline

1. SMBHs evolution: why bother?
2. Dynamical evolution of MBHs:

    Formation and coalescence of MBH binaries

    Gravitational rocket

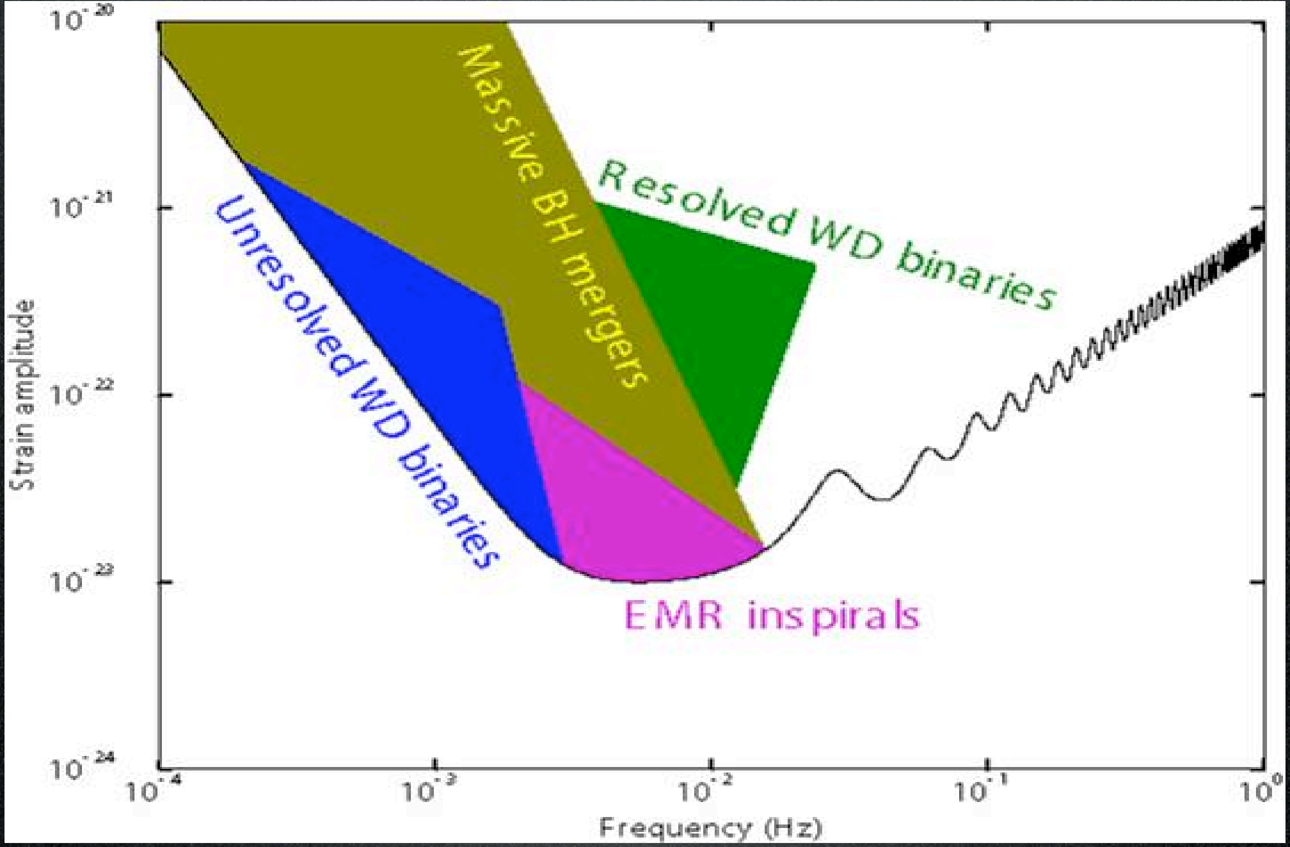
3. MBHs spin
4. Gravitational waves

SMBHs evolution: why bother?

MBH mergers are among the brightest sources for LISA.

MBHs M<10^5 Msun can be detected up to z=15-20.

That's why we care about the cosmological evolution.



WHEN do you make a (super) massive black hole?

The highest redshift quasar currently known

SDSS 1148+3251 at $z=6.4$

has estimates of the SMBH mass

$M_{BH}=2\text{-}6 \times 10^9 M_{sun}$

(Willott et al 2003, Barth et al 2003)

AS LARGE AS THE LARGEST SMBHs

SEEN TODAY, BUT

WHEN THE UNIVERSE WAS 1 Gyr OLD!!!

Hey guys, we have to deal with cosmology...

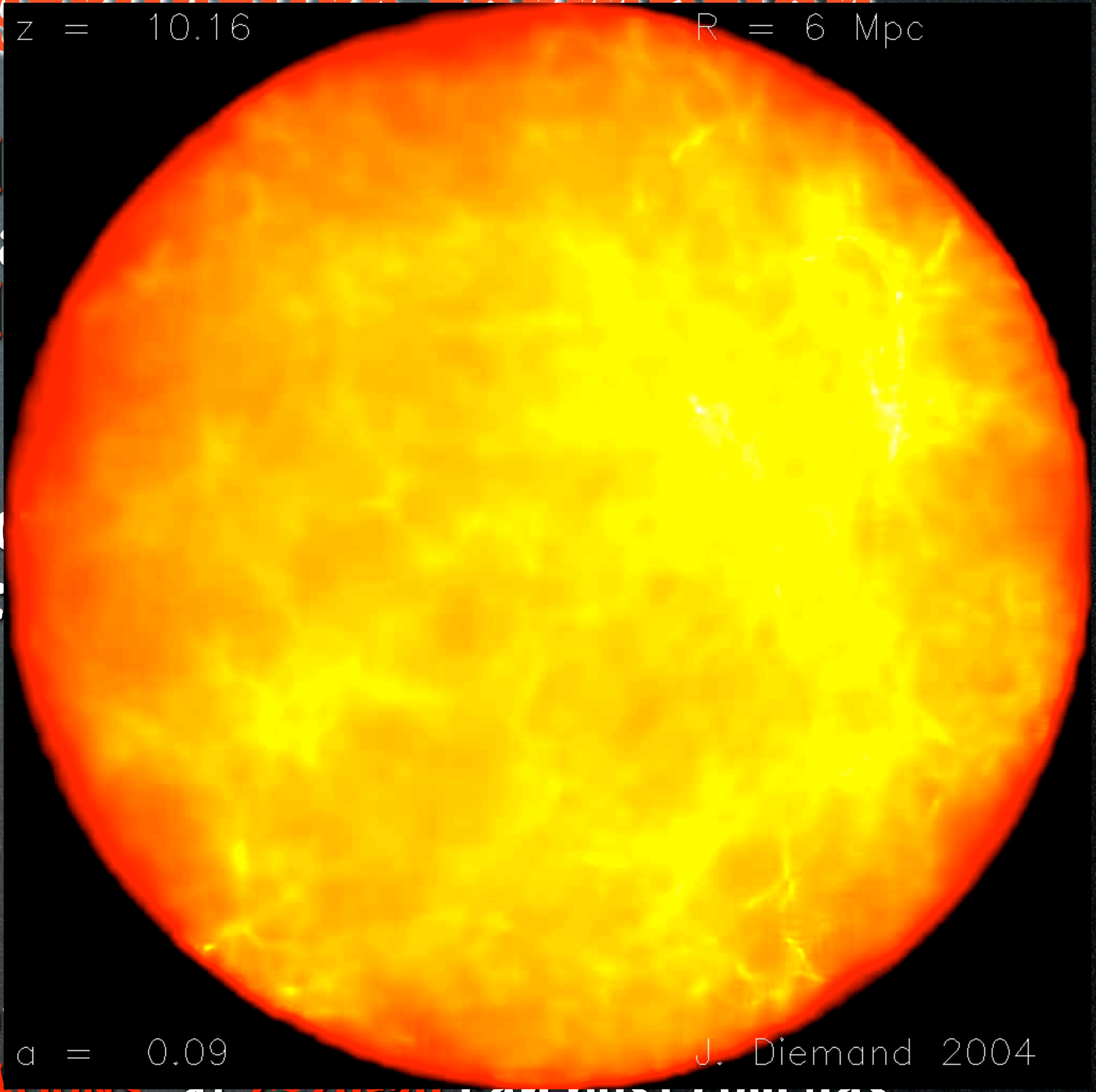
Hierarchical s

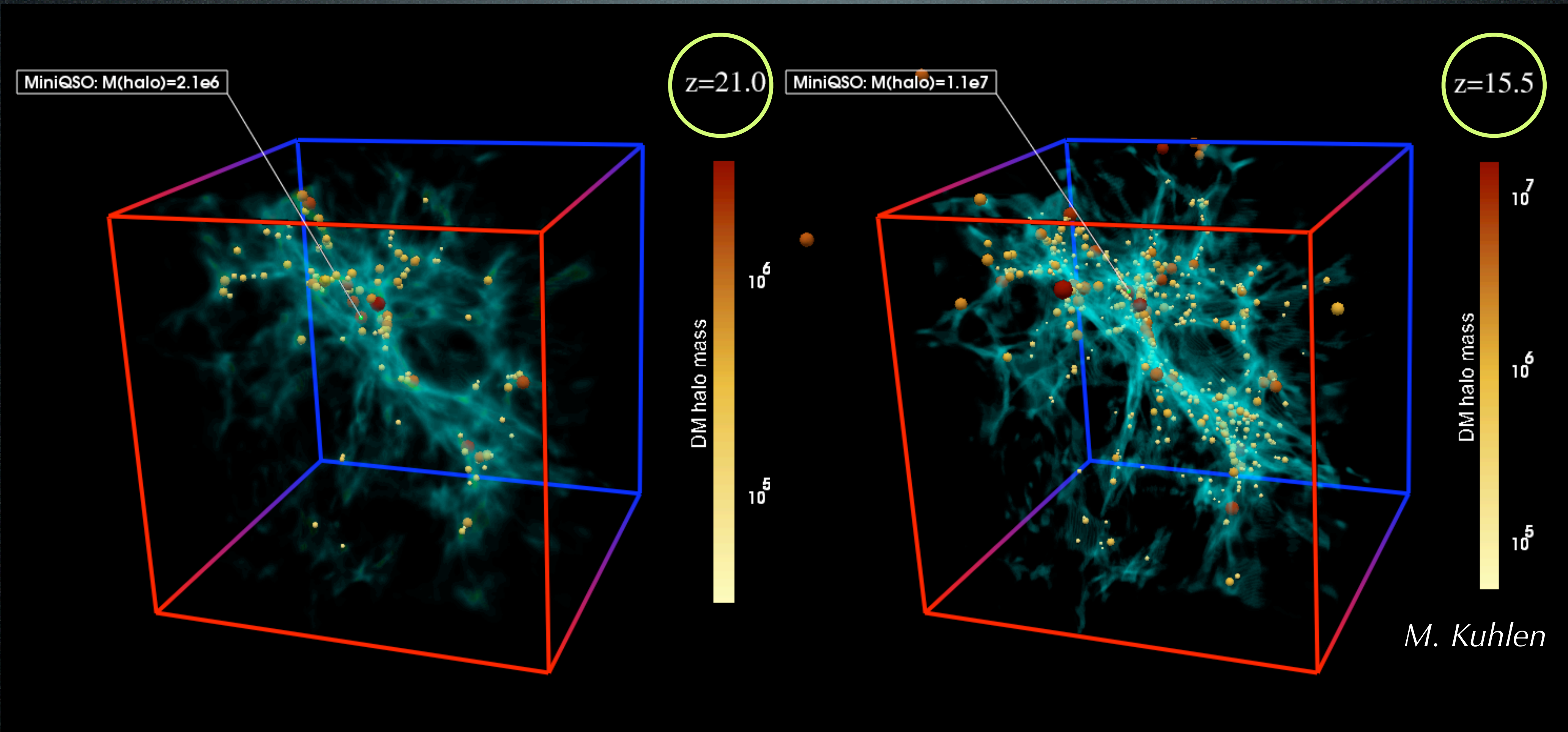
Gravitational instabil
distribution caused m
become gravitationall

The first collapsing hal
more massive systems:

From DM halos

Only a small fraction o
HIGHEST DENSITY FLUCTUA
and eventually stars and/or black holes





Hierarchical Galaxy Formation:
small scales collapse first

BARYONS: need to COOL
only the MOST MASSIVE HALOS, i.e. the HIGHEST DENSITY FLUCTUATIONS at z~20-30

HOW can you make a (super)massive black hole @ z≈10-30?

M_{BH}~100-600 M_{sun}

PopIII stars remnants
(Madau & Rees 2001, Volonteri, Haardt & Madau 2003)

✓ Simulations suggest that the first stars are massive M~100-600 M_{sun} (Abel et al., Bromm et al.)

✓ Metal free dying stars with M>260M_{sun} leave remnant BHs with M_{seed}≥100M_{sun} (Fryer, Woosley & Heger)

M_{BH}~10^3-10^6 M_{sun}

Viscous transport + supermassive star (e.g. Haehnelt & Rees 1993, Eisenstein & Loeb 1995, Bromm & Loeb 2003, Koushiappas et al. 2004)

✓ Efficient viscous angular momentum transport + efficient gas confinement

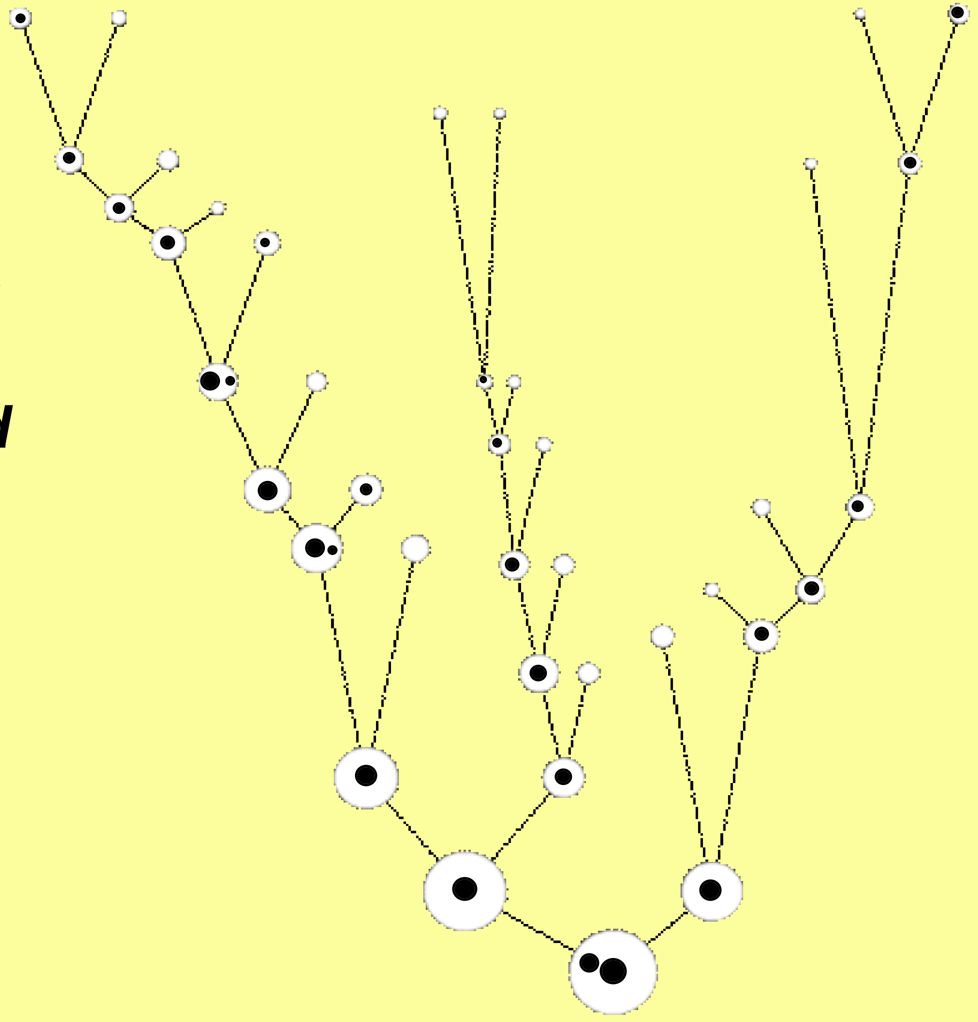
---

Bar-unstable self-gravitating gas + large "quasistar" (Begelman, Volonteri & Rees 2006)

✓ Transport angular momentum on the dynamical timescale, process cascades

THE MODEL

SMBHS are grown from seed pregalactic BHs. These seeds are incorporated in larger and larger halos, accreting gas and dynamically interacting after mergers.



Volonteri, Haardt & Madau 2003

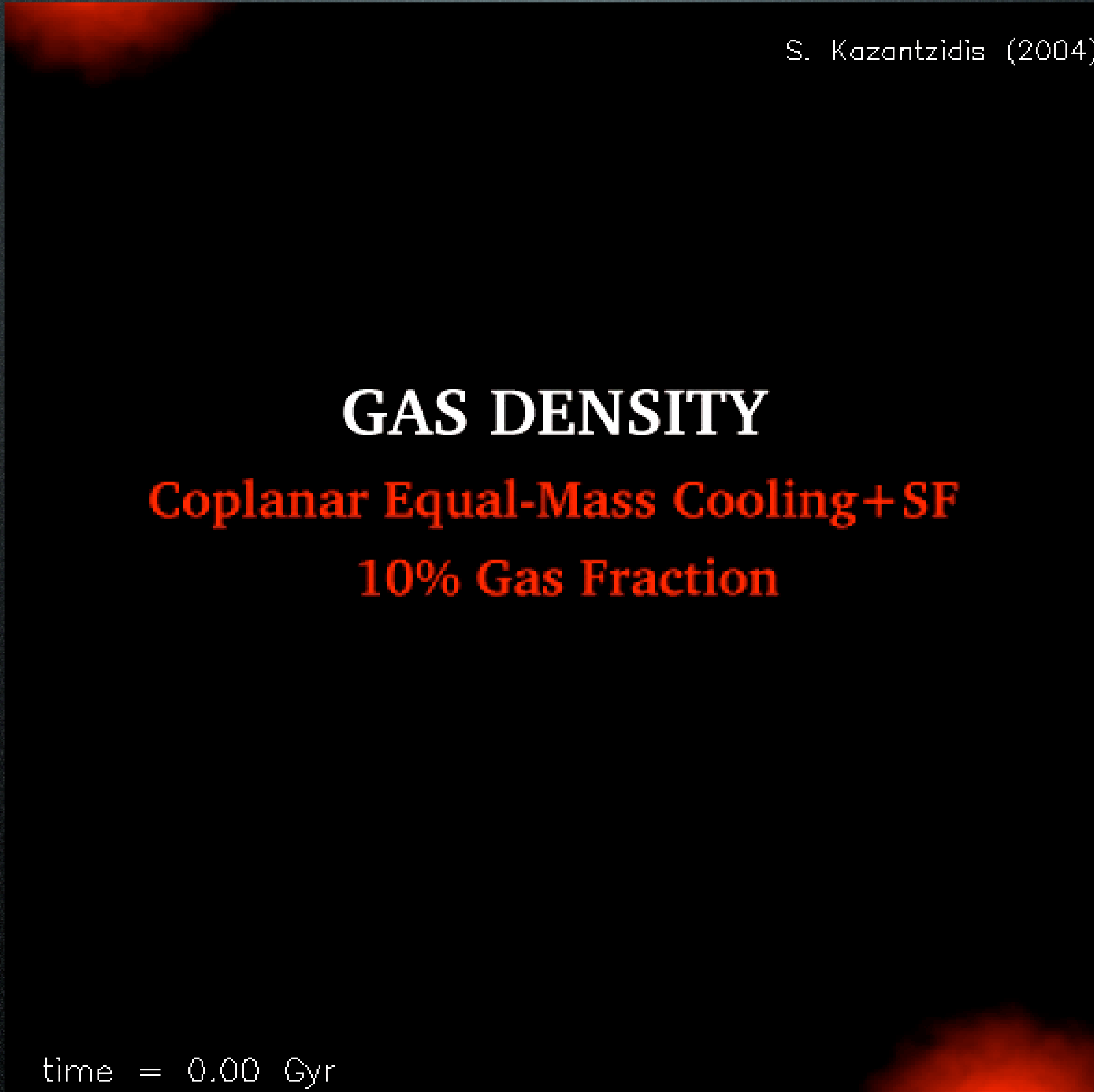
Note: MBH formation happens only in high peaks in the density field. MBHs are biased at birth!

MBHs weddings...

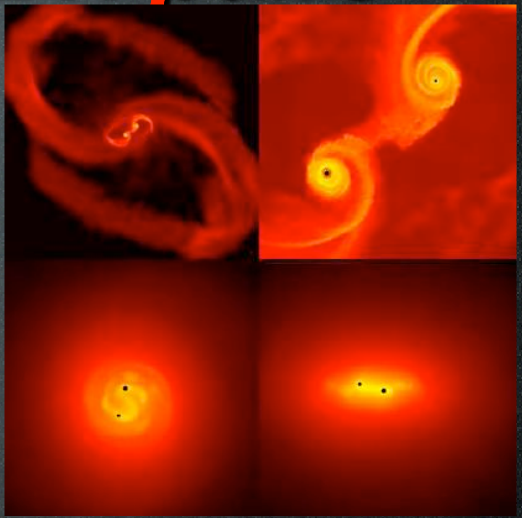
MBH mergers: can we cut a long story short? Most dynamical processes for MBH binaries imply **long merger timescales**. Nature must be much more efficient than our calculations...

... and honeymoons

how MBHs take **long trips**, sometimes never to return


S. Kazantzidis (2004)
GAS DENSITY
Coplanar Equal-Mass Cooling+SF
10% Gas Fraction
time = 0.00 Gyr

Dynamical evolution of BH pairs



1. *dynamical friction*

✓ *efficient only for major (i.e. galaxies with similar masses) mergers against mass stripping*

minor mergers: orbital decay > Hubble time

2. *hardening of the binary*

(Quinlan 1996, Merritt 1999, Miloslavljevic & Merritt 2001)

Dynamical friction can be efficient in driving the two BHs to a separation of order

$$a_h = \frac{G m_2}{4\sigma^2} = 1\,\mathrm{pc}\left(\frac{m_2}{2\times 10^7\ \mathrm{M}_\odot}\right)\sigma_{150}^{-2}$$

GW emission takes over at separation of the order

$$a_{GW} \approx 0.0014\,\mathrm{pc}\left(\frac{M M_1 M_2}{10^{18.3}\ \mathrm{M}_\odot{}^3}\right)^{1/4}$$

Sigurdsson's talk

Physical mechanisms able to shrin

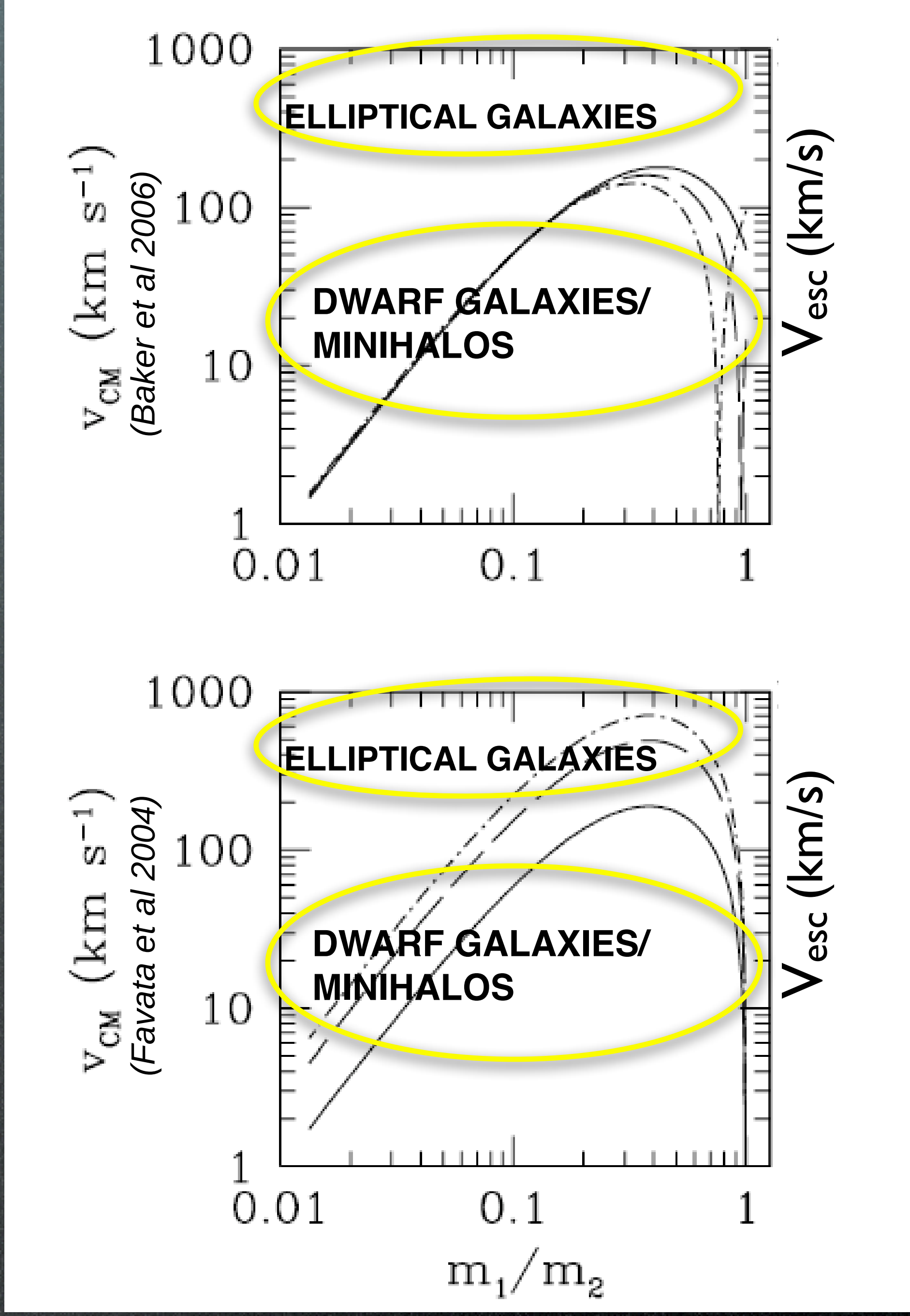
separation of about ***two orders of magnitude***

Gravitational Rocket

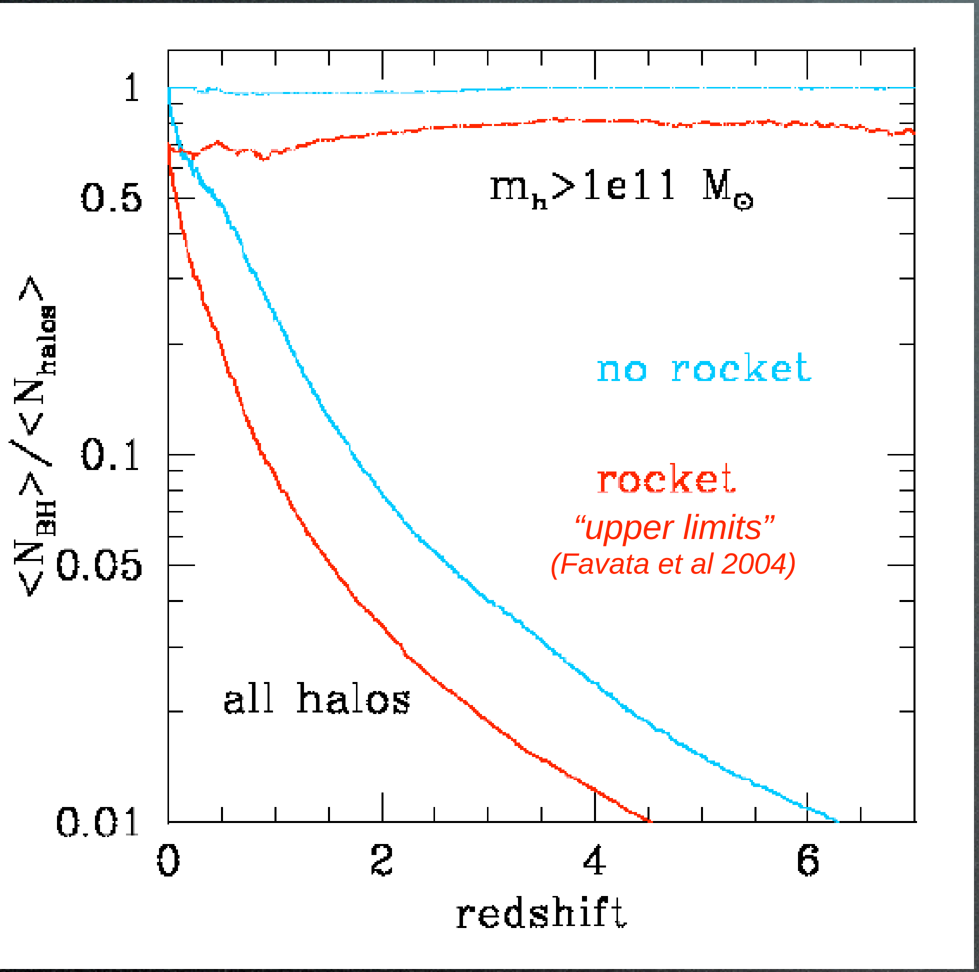
binary center of mass recoil during coalescence due to asymmetric emission of GW

(e.g. Fitchett 1983, Favata et al 2004, Blanchet et al 2005, Baker et al 2006)

Are merging BHs ejected from galaxies?



If mergers do happen efficiently, how much is the gravitational rocket a threat for the SMBH evolution?



… but @ z < 5 it's not a problem

50-80% of galaxies with mass <10^{11} Msun can host a SMBH

>90% for larger galaxies

No real worries for EMRIs…

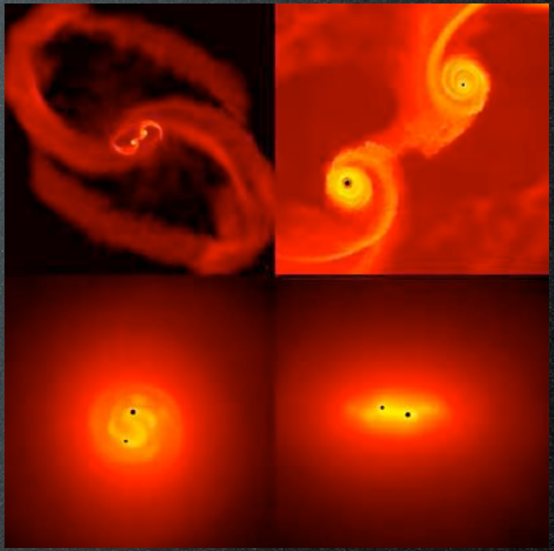
MBH spins

"2 hairs theorem": BHs have mass and spin

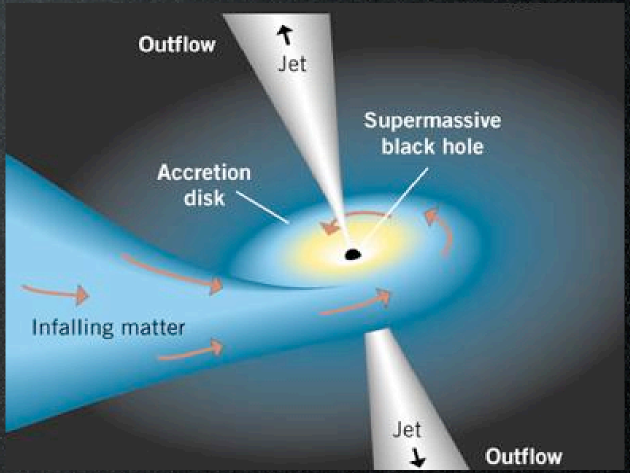
It is very very very difficult to probe MBH spins in the EM spectrum

LISA can help us constrain models of MBH spin evolution

BHs spin is modified by BH mergers and the coupling with the accretion disc



✓ *mergers can spin BHs either up or down in a sort of random walk*



✓ *alignment with a thin disc spins up efficiently on short timescales*

The hierarchical evolution predicts typical BH spins close to maximal at least at z>1

Volonteri, Madau, Quataert & Rees 2005

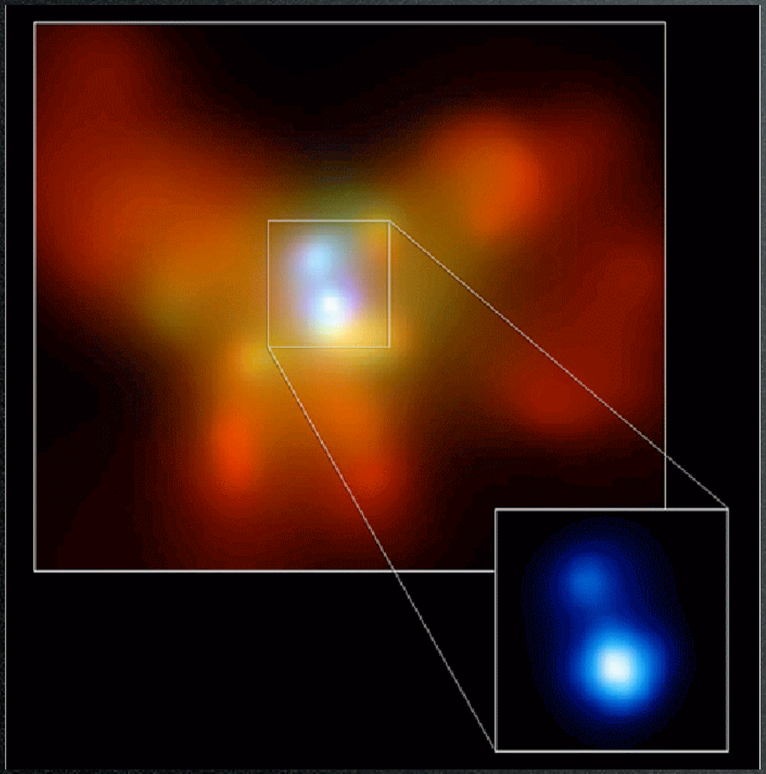
SMBH mergers and their detectability

EM bands:

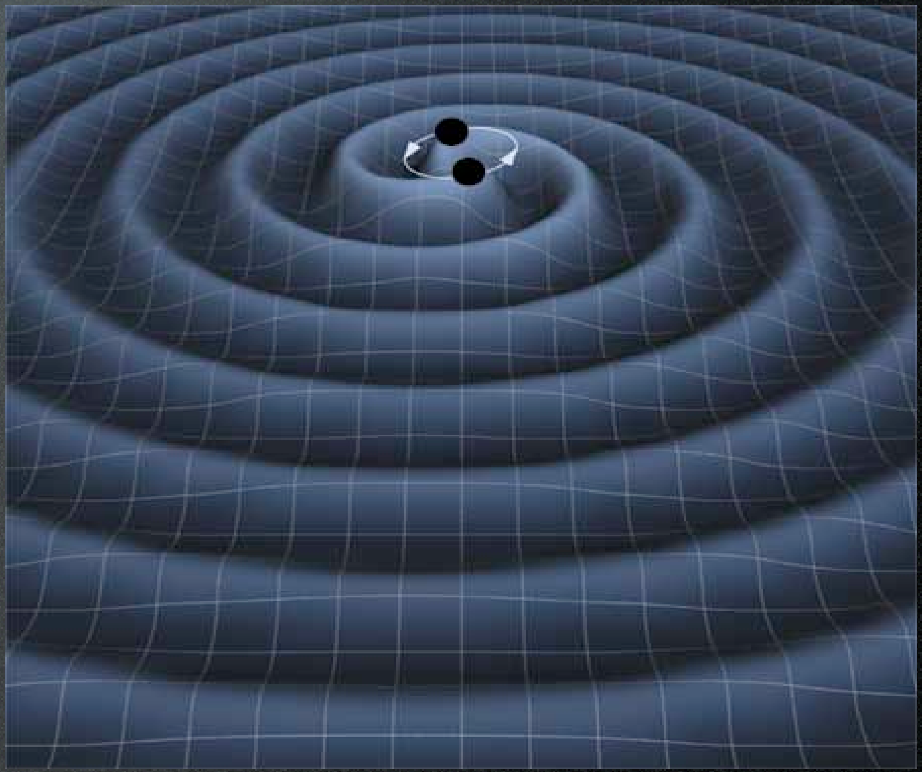
- ✔ MBHs must be accreting
- ✔ dust/obscuration
- ✔ resolution

GWs:

- ✔ Binary hang-ups?
- ✔ detections even @ high-z
- ✔ data analysis

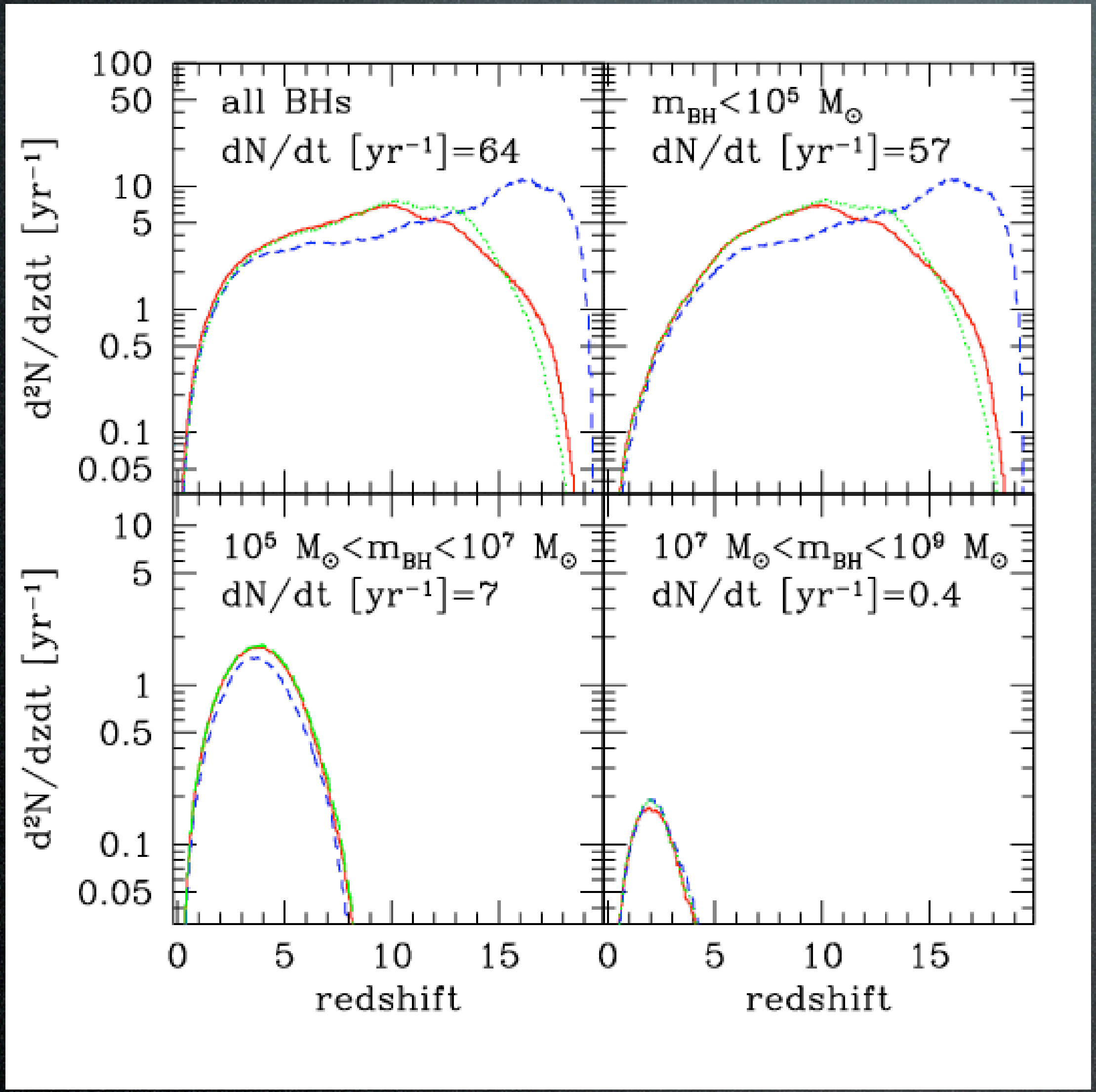


NGC 6240 Komossa et al.



SMBH binary merger rate

Sesana et al. 2004

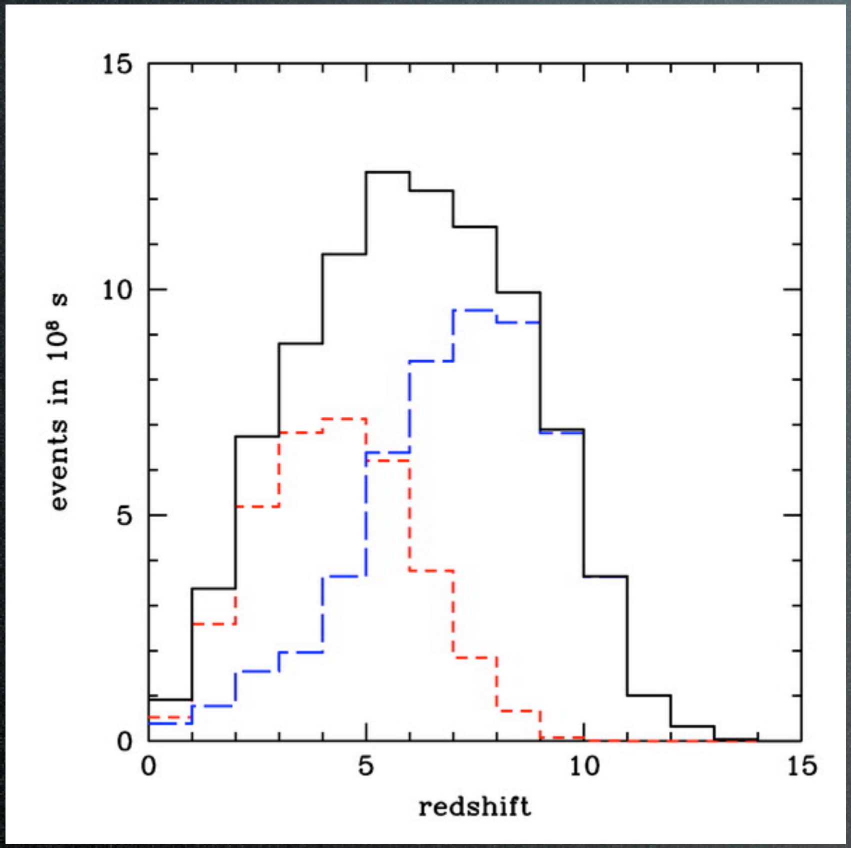


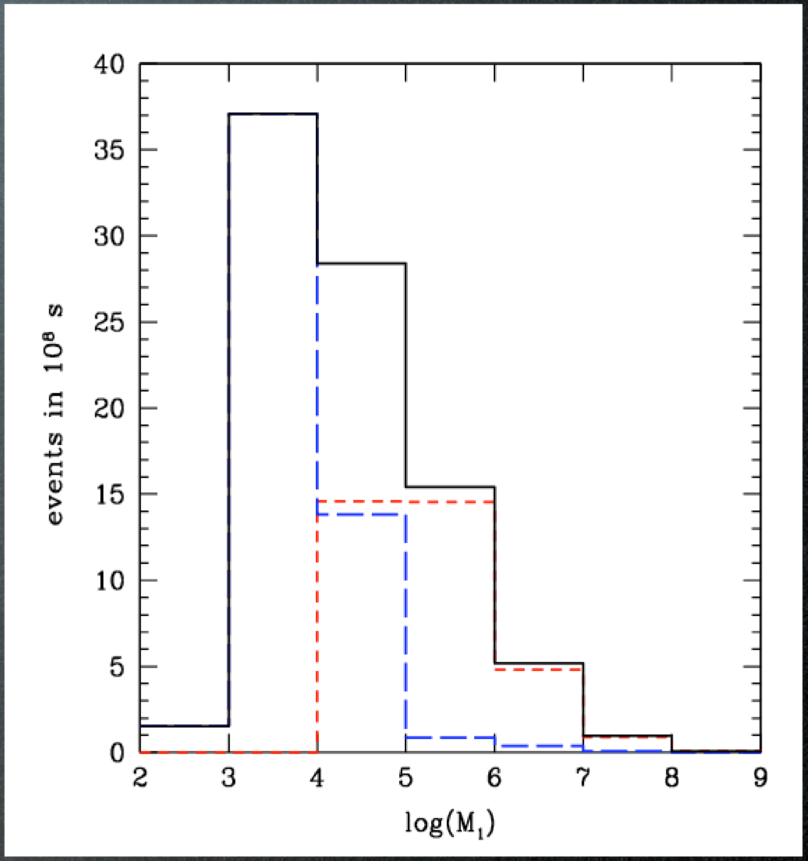
Seeds: PopIII stars remnants

Long/short merging timescales

Resolvable events in 3 years

Sesana et al. 2004, 2005





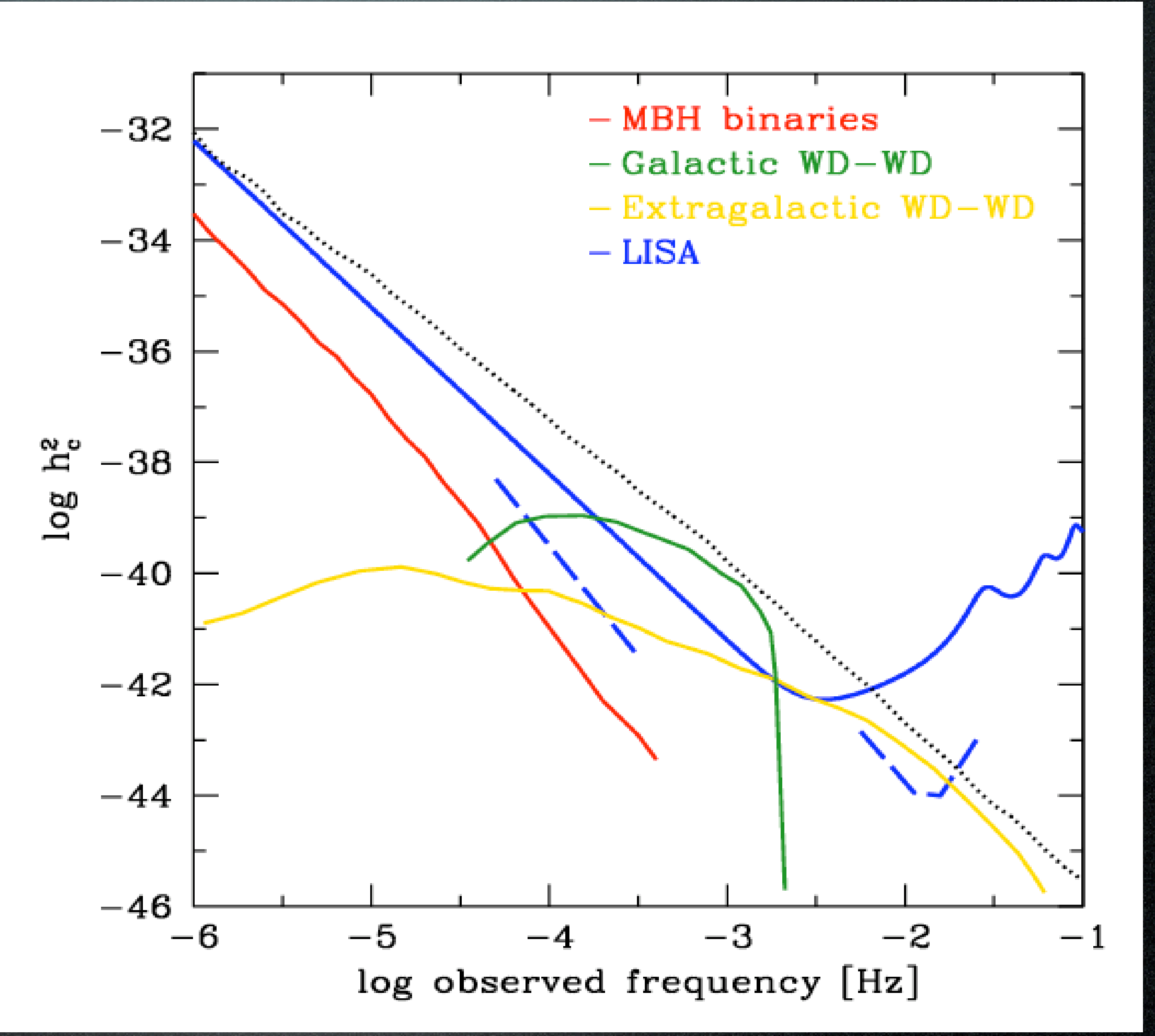
Inspirals: longlasting wide binaries, small frequency change

Bursts: binaries coalescing during the observation period

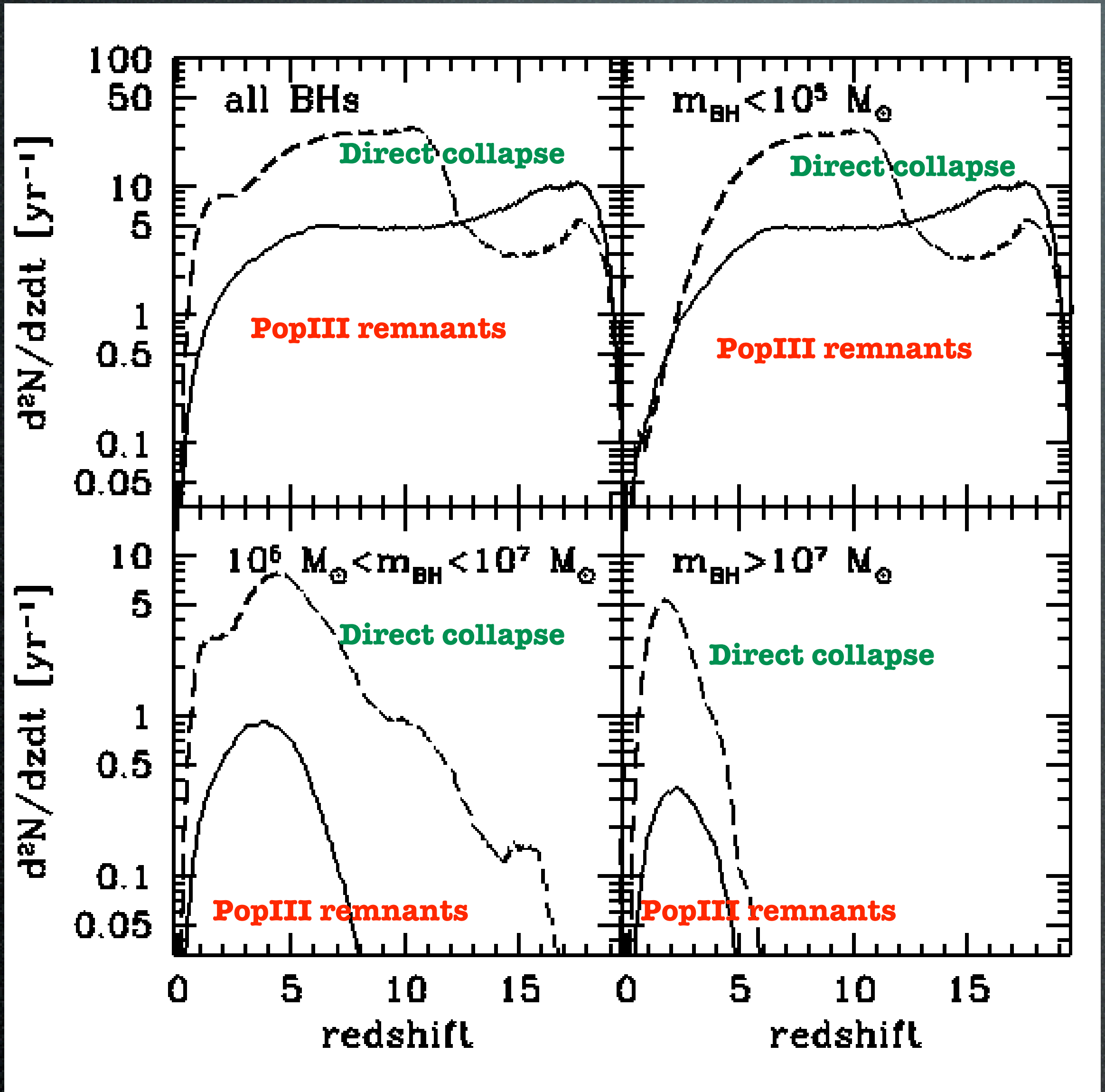
Typical masses ~10^3-10^6 M_{sun}

Typical mass ratio ~ 0.1

Very low confusion noise!



SMBH binary merger rate



Uncertainties in MBH seeds formation

Comparison:

Volonteri, Haardt & Madau 2003

PopIII remnants

vs

Koushiappas et al 2004

Direct collapse

Use the same dynamical evolution (including MBH binaries hardening)

Models comparison

a large parameter space for existing predictions....

Reference	Rate (events/year)	Redshift range
Haenhelt 2003 [24]	0.1-1	$0 < z < 5$ (gas collapse only)
	10-100	$z > 5$ (hierarchical buildup)
Menou *et al.* 2001 [32]	10	$z < 5$
Rhook and Wyithe 2005 [34, 33]	15	$z \sim 3 - 4$
Sesana *et al.* 2004 [35, 36]	35	$2 < z < 6$
	9	one BH with $M > 10^5 M_\odot$
Enoki *et al.* 2004 [37]	1	$z > 2$
Islam *et al.* 2003 [38]	$10^4 - 10^5$	$z \sim 4 - 6$
Koushiappas and Zentner 2005 [39]	stochastic background	mostly $z \sim 10$, down to $z \sim 1$ (see their Fig. 3)

from Berti 2006

Summary

SMBHs can be built up from seeds dating back to the end of the cosmological dark ages

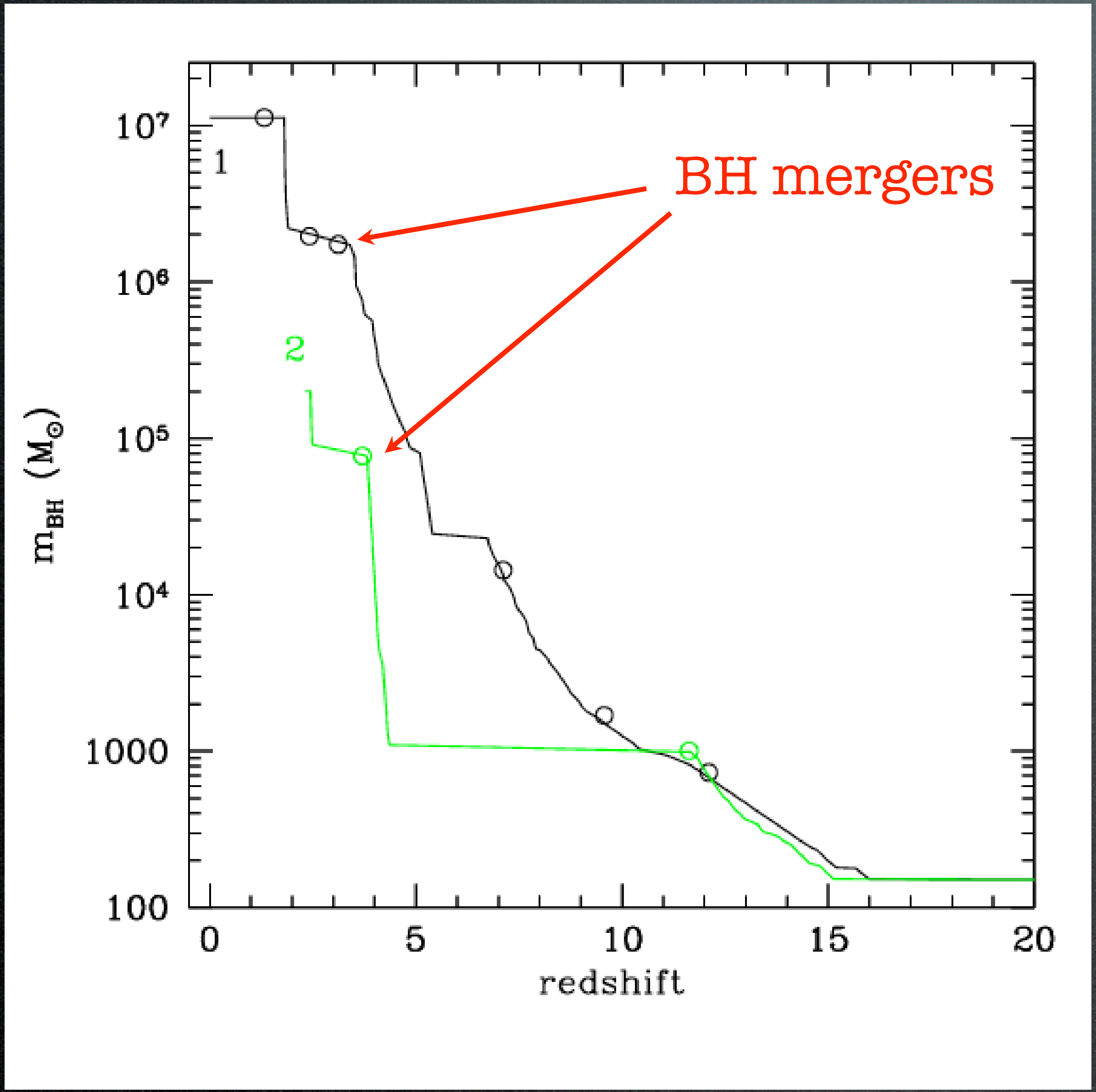
✔ *seed MBHs are born in the highest density fluctuations at high z*

✔ *MBHs typically rapidly spinning*

✔ *mergers unimportant for the mass build-up @ low-z*

✔ *dynamical and gravitational interactions can displace MBHs … BUT they don't hinder the assembly of SMBHs*

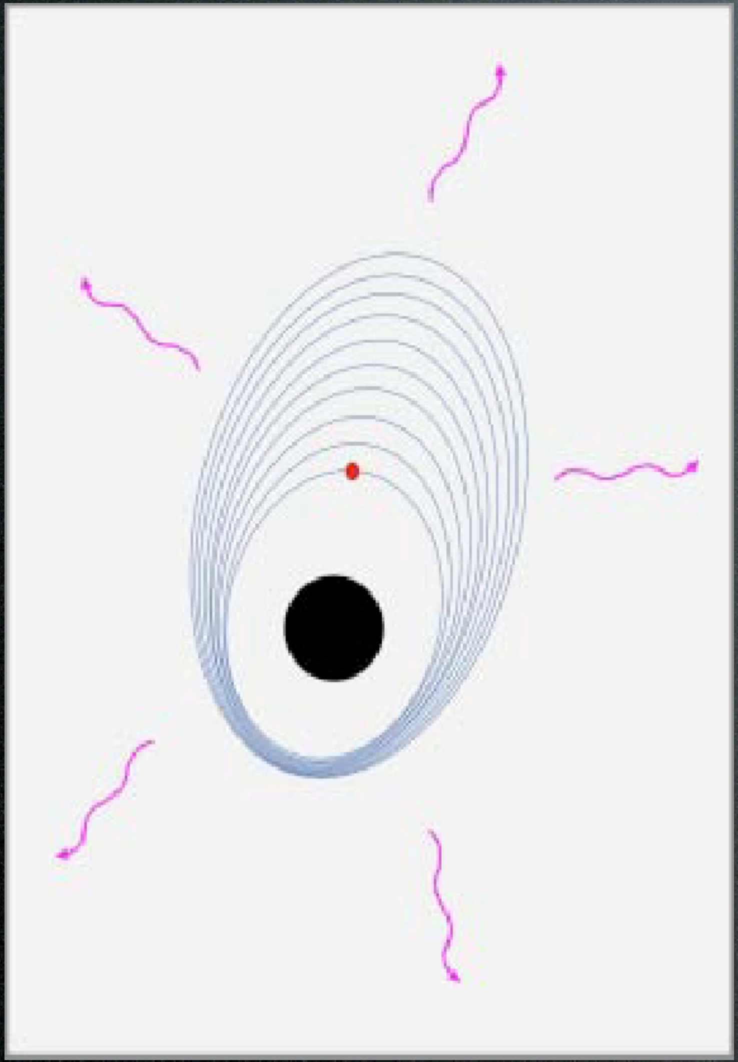
Folding in mergers and accretion in a hierarchical model...



✓ *MBH mergers are rare events, as they require a merger between two galaxies BOTH with a central MBH*

✓ *not ALL MBHs experience a merger in their lifetime, only ~40-50%*

Extreme mass ratio inspirals



Inspiral of a compact object (WD, NS, BH) into a supermassive black hole in the centre of a galaxy.

LISA can see $10M_{sun} + 10^6 M_{sun}$ inspiral out to z~2 → can probe SMBH spin evolution if event rate is high enough!!

For a typical event with SNR~30, determine parameters with errors (Barack & Cutler, Creighton et al.)

$\Delta M \sim 2 \times 10^{-4}$
$\Delta(S/M^2) \sim 10^{-4}$
$\Delta(\ln m) \sim 10^{-4}$
$\Delta(\ln D) \sim 0.05$